Preprint
UCRL-JC-142297

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This article was submitted to
28th European Physical Society Conference on Controlled Fusion and Plasma Physics, Madeira, Poland, June 18-22, 2001

June 13, 2001

U.S. Department of Energy

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1. Introduction

SSPX (Sustained Spheromak Physics eXperiment) was constructed to investigate the key physics issues of buildup and sustainment of spheromak plasmas with elevated electron temperature [1]. Long pulse buildup to high magnetic field and temperature, at modest gun current, may point the way to a potentially simpler and more compact fusion reactor. Reported here are T_e measurements in new magnetic flux geometries, results from sustainment experiments with ~1ms pulses, and power balance modeling of buildup. The experiment uses coaxial gun injection. Tungsten coated walls reduce plasma impurities. The magnet coil set has been upgraded from 3 (base set) to 9 coils (bias coils) to control the vacuum magnetic flux geometry within the gun and flux conserver ($a=l$=0.5 m). SSPX is powered by a formation bank (0.5 MJ, τ_{rise}~0.15 ms) and a sustainment bank (1.5 MJ, τ_p~1 ms). Radiated power <20% of input power and the burn-out of low Z impurities (C, N, and $O^{+Z\leq 5}$) have been achieved using bakeout, wall conditioning, and titanium gettering [2]. These techniques have produced long decay time plasmas and electron temperature > 100 eV.

2. Electron Temperatures in SSPX

In a nearly sustained discharge in modified flux (partial flux core geometry) with modest gun current ($\lambda_g/\lambda_0 \approx 1$) during sustainment, Thomson scattering has measured n_e and T_e profiles peaked near the magnetic axis (T_{e0}=120 eV, $n_{e0}=1\text{x}10^{20}$ m^{-3}, and β_{e0} *(local)*~5%) [3]. Here, ϕ_g is the gun flux, $\lambda_g=\mu_0 I_g/\phi_g$, and λ_0 =10 m^{-1} is the flux conserver eigenvalue. Within measurement errors, these profiles depend on the poloidal flux, computed from CORSICA equilibrium fits to a wall poloidal magnetic probe array [4]. They are consistent with good confinement flux surfaces or very long field line connection lengths to the wall (~100 m). Low magnetic turbulence, preserving good flux surfaces, was probably important for these results.

Using the bias coils to vary magnetic flux geometry, the injected gas required for breakdown and spheromak formation was reduced a factor ~6. Preliminary investigations

* Work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

explored flux core geometries and a case with the limiting flux boundary surface parallel to the wall. This extends the density range during sustainment from n_e~10^{20} m^{-3} down to ~$0.2x10^{20}$ m^{-3}, resulting in a large increase in core T_e at lower density [Fig. 1]. In the plot density was divided by the (poloidal field)^2 at the midplane wall and $B_n=B_p/0.2$ was normalized to 0.2 T. Whether this data is evidence of a beta limit is under investigation. Measurement errors in T_e at lower density are uncertain because of plasma bremsstrahlung. Diagnostic improvements are underway.

3. **Spheromak Formation and Sustainment**

SSPX experiments have investigated 1) short pulse, high current formation and 2) sustainment and buildup at longer pulse and lower current. Peak poloidal field scales directly with peak gun current (Fig. 2), using either one or two pulses (second pulse at higher current). The ratio B_p/I_g does not appear sensitive to vacuum magnetic flux geometry.

Long pulse buildup, followed by sustainment, is clearly the preferred way to obtain higher field because lower current and power are required. Asymmetric turbulent fields (with m=1), sufficiently large for dynamo current drive to buildup and sustain the plasma, must not also destroy confinement. Global-mode mhd fluctuations, observed on wall magnetic and wall current Rogowski probes, are prominent in SSPX. A kinking of central column open flux (m/n=1/1, 'dough hook') occurs during formation and sometimes during sustainment. Although spheromak magnetic field increases with this mode, large mode amplitude may not be favorable for good confinement. Higher order modes (m/n=1/2, 1/3, 1/4) and shorter wavelength turbulence are also seen during sustained discharges with low levels of turbulence.

Understanding buildup and the associated turbulence is the key issue for SSPX. For buildup we need to understand the relation between gun impedance, the fraction of gun power coupled into the 'good confinement' spheromak core, and the role of turbulence in core losses.

4. **Power Coupling and Spheromak Buildup**

We have used power balance and a gun impedance model proposed by Fowler [5] to calculate buildup in SSPX. Fowler models the gun voltage as $V_{gun} = V_{sh}+V_{R(edge)}+V_{sp}$, where $V_{sh} =\gamma\ T_{e(edge)}$ (γ=constant) is the net gun sheath voltage drop and $V_{R(edge)}$ is the dissipative resistive voltage drop in the plasma edge. To drive the equilibrium toward the Taylor state, V_{sp} models periodic turbulent transport (by island overlap and reconnection) of inductance energy (related to current flow in the plasma edge) into the spheromak core. $V_{sp}\propto\kappa I_g[1-(I_0/I_g)^2]$ [6] is excited above a gun current threshold, $I_0=\lambda_0\phi_g/\mu_0$. The gun power coupled into the spheromak is defined by $P_{sp}=\varepsilon_P P_g$, where $\varepsilon_P=V_{sp}/(V_{sh}+V_{R(edge)}+V_{sp})$. $\varepsilon_P(I_g)$ was determined from a fit of the parameters γ and κ to measured gun voltage during sustainment for a group of SSPX modified flux discharges with fixed ϕ_g and varying I_g. Typical values are V_{sh}~150 V, ε_P ~0.2-0.3, and $T_{e(edge)}$ ~20 eV near the geometric axis.

Magnetic energy buildup was calculated from solution of $dW_m/dt=\varepsilon_P P_g-W_m/\tau_{Em}$ using gun current and voltage for a spheromak discharge. Fig. 3 compares the model and CORSICA equilibrium fits to magnetic probe data for discharge 4325. We obtain fair agreement with CORSICA for τ_{Em}~1-2 ms. Although T_e data is unavailable for this discharge, core temperatures T_e~20-40 eV are expected at the high density (~2-3x10^{20} m^{-3}) measured by CO2 interferometry. The inferred value of τ_{Em} is consistent with Spitzer resistivity in this range of T_e.

An inductor to extend the gun pulse at constant current will soon be available in SSPX. Using the results from Fig. 3, we project buildup to higher magnetic energy [Fig. 4]. Using the bias coils to operate at lower density, we might expect higher T_e and τ_{Em}. However, the gun voltage is lower than for modified flux and we have not tested the model for bias coil discharges.

5. **Summary**

Our results have shown *driven* spheromak plasmas with T_e>100 eV and an expanded range of density and temperature that is accessible with control of the magnetic flux geometry. Installation of a long pulse inductor will allow investigation of buildup and sustainment for longer duration. As the magnetic field rises, an implication of the Fowler model is a reduced plasma edge cross-section carrying the gun current. This increases edge dissipation, thereby reducing ε_P and eventually limiting field buildup. Changes in gun geometry to increase the edge cross-section might reduce this effect. Better understanding of turbulence and coupling of gun power to the spheromak are probably necessary for success of these experiments.

References

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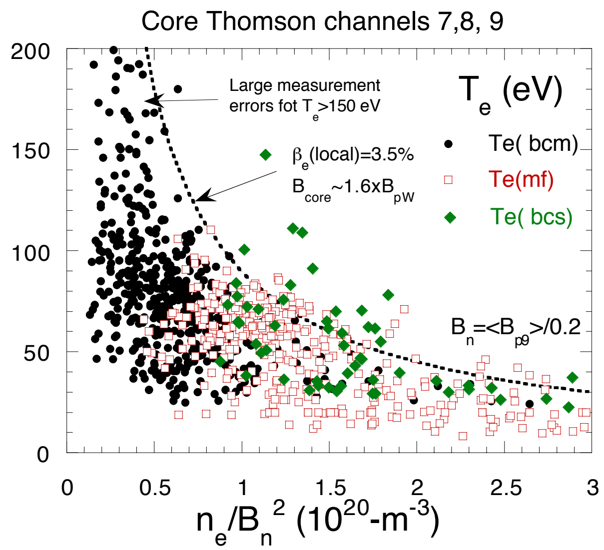


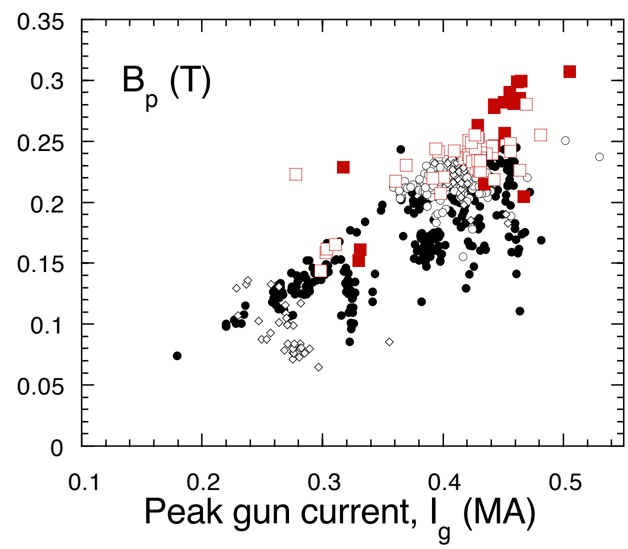
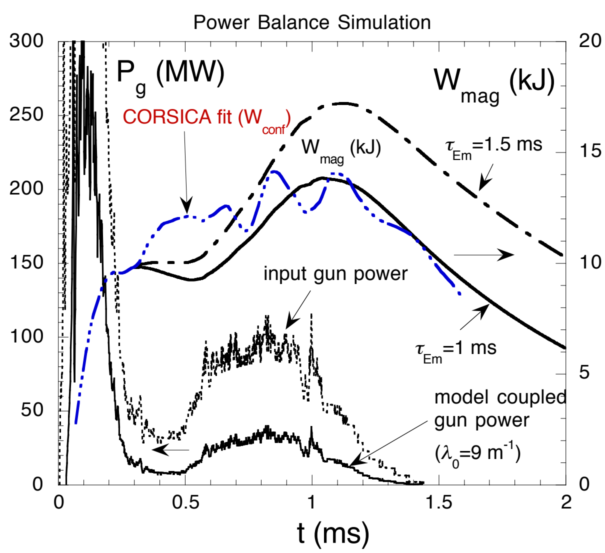


Fig.1 Accessible range of core T_e and n_e for several vacuum flux geometries. B_p(wall)~0.2 T is the nominal value for most discharges.

Fig.2 Dependence of the midplane wall poloidal field on peak gun current during spheromak formation.



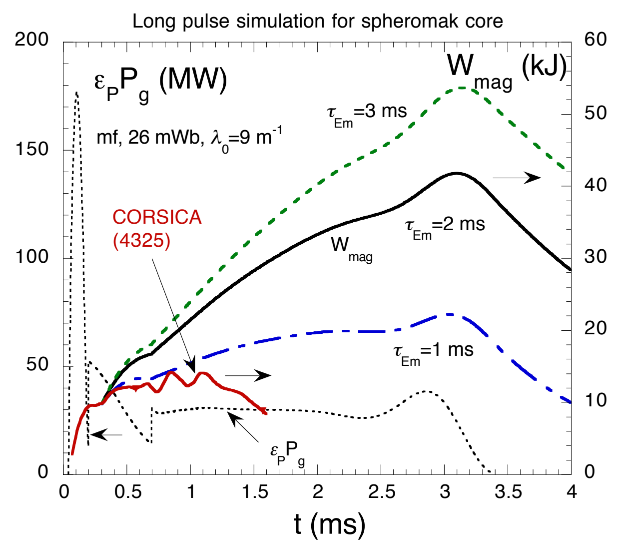


Fig.3 Core magnetic energy from CORSICA fit to magnetic probes (discharge 4325) and energy computed from Fowler power coupling model and magnetic decay time.

Fig.4 Projected buildup with long pulse current using Fowler model for 26 mWb modified flux geometry.